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Experimental measurement of dynamic concentration of nanofluid in laminar flow

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ABSTRACT

Nanofluid is thought to have a potential enhancement in heat transfer behaviour of fluid. The nanoparticle concentration in nanofluid is one of the most important factors that affect the nanofluid behaviour. The static concentration was applied in the researches under flowing condition. In this paper, Nuclear Magnetic Resonance (NMR) scanning was applied to study the dynamic concentration of nanofluid flow in pipe. The experiments were carried out with ferrofluid under different concentration and temperature. A new parameter T_2^* was introduced in the study. Experiments were carried out to obtain the T_2^* of nanofluid in the pipe. An empirical equation based on T_2^* and temperature was proposed to calculate the concentration of nanoparticles. Then, experiments were carried out with flowing ferrofluid in pipe. The dynamic concentration was calculated with the empirical equation. It has a highest concentration near the pipe wall. The concentration decreases from the wall to the pipe centre. Furthermore, the experiment result also gives out a chance to investigate the mechanism of nanoparticle movement in laminar flow with the concentration gradient along radius.

1. Introduction

Nanofluids are mainly defined as stable suspensions with nanoparticles less than 100 nm in diameter well disperse in the carrier fluid. It is first proposed by Maxwell in 1873 [1]. Since the thermal performance of the solid particles is higher than carrier fluid, Maxwell expected the nanofluids could have a better thermal performance. However, it was until 1995 that Chol tried to use nanofluids as working agents in heat transfer [2]. Since then, nanofluids have attracted wide attention from industrial cooling [3], nuclear power generation [4], automotive [5,6], fuel cell [7], drag delivery [8], cancer therapy [9], detergency [10], dynamic sealing [11], etc. [12,13]. Especially, some nanofluids with specific particles such as magnetic nanofluids, mainly known as ferrofluid, contain strong and unique properties, which may have wider usage in industry for being sensitive to external magnetic field.

The concentration of nanofluid is one of the most important factors that determine the characteristics of nanofluid. For the high surface to volume ratio, nanoparticles suffer from a non-ignorable Van der Waals force and surface tension, leads to a tendency of gathering together in nanofluid [14]. This makes it even worse in flowing nanofluid for the boundaries could generate a strong gathering tendency within the nanoparticles. And nanoparticle is so small in size that it will be affected by Brownian movement itself and the fluid clusters around it [15].

The uneven dynamic concentration will affect the behaviours of nanofluids especially heat transfer. The concentration of nanofluid is always assumed as equal in these researches for the lack of measurement methods, which is measure in static state and observed from machines such as Transmission Electron Microscopy (TEM) before the experiment [16–19]. However, the heat transfer behavior is closely related to the specific heat and conductivity of nanofluid, which is decided by the nanoparticle concentration of nanofluid. The conductivity always has optimized concentration where conductivities reach maximum, while the specific heat considered always going down as concentration increases [20].

Even though the heat transfer performance of nanofluid can be treated as a whole, it may still be possible that circumstances may be different and affect the gradient and cause different performance under the same concentration, which makes the real

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Nomenclature

M	nuclear spin magnetization (A/m)
T	temperature (°C)
T_1	longitudinal relaxation time
v	flow velocity (mm/s)
ΔB_0	local varying field strength difference
t	time (ms)
S	non-dimensional Signal Strength
T_2	transverse relaxation time
k	slope of decaying line

Greek letters

ϕ	volume concentration (%)
λ	thermal conductivity (W/(m·K))
γ	gyromagnetic ratio

Subscripts

xy	surface formed by x and y axis
ef	effective thermal conductivity
f	fluid
z	z axis
eq	equilibrium
p	particle

concentration in dynamic very different from the one observed in static using TEM. And also the heat transfer efficiency of nanofluid is decided by the conductivity of nanofluid near the boundary surface. So, the concentration of nanofluids cannot be assumed as equal under flowing condition.

Therefore, the dynamic concentration of cross section along the flow channel is necessary for analysing the performance of nanofluid. A new method for dynamic concentration measurement, Nuclear Magnetic Resonance (NMR), is introduced to measure the dynamic concentration distribution of cross section of flow channel. A new overall parameter from NMR, which is easily detected and has a unique relation with concentration, temperature and velocity etc., is firstly introduced in the measurement of dynamic nanoparticle concentration with NMR in this work. Then a method to calculate the dynamic concentration distribution of cross section with this parameter is developed. The experiments are carried out with ferrofluid (a magnetic nanofluid using Fe_3O_4) in the pipe under different concentration and temperature. The dynamic concentration of nanoparticles is calculated with the method developed in this paper. The thermal conductivity of ferrofluid flowing in the pipe is also studied with the dynamic concentration obtained with the method in this paper.

2. NMR theory

NMR is a powerful and theoretically complex analytical tool. It was first described and measured in molecular beams by Isidor Rabi in 1938, later Felix Bloch and Edward Mills Purcell expanded the technique for use on liquids and solids in 1946. NMR is developing as one of the most important method in medical research [21,22]. The NMR method has also been applied to study water migration in plant [23].

NMR performances experiment on the nuclei of atoms, not the electrons. Longitudinal (or spin-lattice) relaxation time T_1 and transverse (or spin-spin) relaxation time T_2 are the two basic parameters in NMR. T_1 is the decay constant for the recovery of the z component of the nuclear spin magnetization towards its thermal equilibrium value, and T_2 is the decay constant for the component of perpendicular magnetization field [24]. T_2 is the key relaxation time in this paper. In nanofluid, the nuclei, mainly hydrogen atom in water, would release signals during its magnetization process, which would decay away when it goes back to equilibrium distribution, as is shown in Fig. 1. So T_1 and T_2 become the most important relaxation times in the progress with different tissues or fluid situations. In general,

$$M_z(t) = M_{z,eq} - \left[M_{z,eq} - M_z(0)\right]e^{-t/T_1} \quad (1)$$

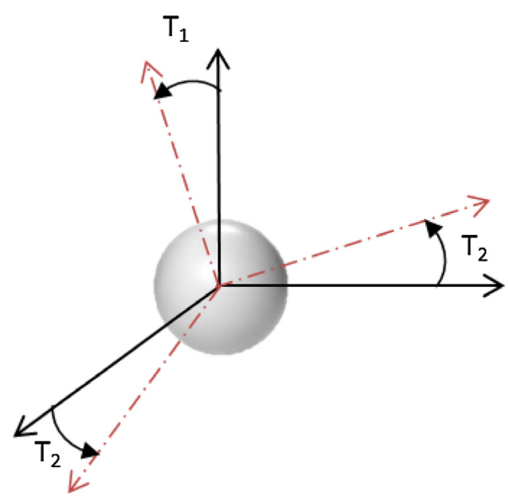

Fig. 1. Relaxation time of resonance signals from nuclei.

$$M_{xy} = M_{xy}(0)e^{-t/T_2} \quad (2)$$

where M is affected by external magnetic field.

So when the nuclei are going back to equilibrium, the signals it releases will be detected by NMR machine, recorded as the signal intensity S. By taking logarithm of the T_2 signals intensity S in Eq. (2), the equation is as below,

$$\log(S) = -t/T_2 + \log(M) \quad (3)$$

The slope is,

$$k = -1/T_2 \quad (4)$$

The log(S) has a linear relation with time t in Eq. (3), for T_2 is a decay constant related to the fluid characteristics. So the T_2 performs much better than T_1 based on this point. In real case, the distribution of resonance frequency can lead to a loss of signal intensity, which causes the signals decaying faster than theory, then a smaller T_2 is measured, which is T_2^*,

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{1}{T_{in\,hom}} = \frac{1}{T_2} + \gamma\Delta B_0 \quad (5)$$

Then T_2^* is used to instead T_2 in the following discussion. So the concentration ϕ measured by NMR are related to T_2^*, T and v,

$$f(\phi, T_2^*, T, v) = 0 \quad (6)$$

where ϕ is concentration, meaning ϕ = 0.1 refers when 0.1% volume for example.